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X-ray emission from Bi^{50+} to Bi^{71+} ions incident on a gold surface

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Bi ions with charge states $q = 50$ to 71 from the Livermore National Laboratory's EBIT were accelerated to energies of $q \times (7$ keV) and directed to a gold target. Using a Si(Li) detector, two families of X-rays were observed, one of these in the range of 750–2000 eV and the other between 2500 and 6000 eV. Both families are found to shift to higher energies with increasing incident ion charge state. The lower energy group which dominates the spectra for lower incident charge states is attributed to the filling of vacancies in the N shell while the higher energy group, which predominates for the higher incident charge states, is attributed to the filling of M-shell vacancies. M X-rays are observed even for those incident charge states for which M vacancies are not expected. A similar result observed for U ions incident upon a Be target was attributed by Schuch and coworkers to a dielectronic excitation mechanism.

1. Introduction

The availability of relatively slow-moving, highly charged ions now allows new experiments which probe the interactions of the electronic structures of these ions with surfaces. It has been shown that these interactions create hollow atoms [1] and can result in the emission of unusual X-rays and electrons [2–5]. The present investigation is the second in a series which studies the X-rays emitted when metal surfaces are struck by ions from the Lawrence Livermore National Laboratory's Electron Beam Ion Trap (EBIT). In the first of these experiments, U^{q+} ions with $q = 61$–73 impacted the Be window of a Si(Li) detector and X-rays from the filling of the U M shell were observed [5]. A surprising result was the detection of M X-rays from U ions having charge states in the range of 61–64, since it is only for charge states greater than 64 that M-shell vacancies are expected to exist. The presence of these X-rays was attributed to a dielectronic excitation mechanism in which uranium 3p or 3d electrons are excited, providing a vacancy which is then filled by an X-ray transition. In that experiment it was postulated that the highly charged ion is mostly neutralized before reaching the surface, but that the captured electrons are in a "hollow-shell" configuration which does not have the time to relax before the ion reaches the surface. On reaching the surface, many of the loosely bound electrons are lost and others from the solid are captured into lower n states. For charge states higher than 64, X-rays might be produced by straightforward radiative filling of vacancies. The M X-rays observed for lower charge states were then attributed to a dielectronic-type of excitation of the 3p or 3d electrons during collisions with the solid. One purpose of the present experiment was to observe whether or not a similar effect might be observed for Bi ions, for which the projectile is not expected to have initial M vacancies unless q is greater than 55. The use of a gold rather than a Be target also makes vacancy production by molecular-orbital promotion possible.

2. The experiment

Bi ions with charge states in the range of $q = 50$–71 from the Livermore National Laboratory's EBIT were accelerated to energies of $q \times (7$ keV) and were directed to a gold target. The operation of the EBIT and extraction of ions from it is described in refs. [6,7]. By adjusting the electron beam acceleration voltage and other source parameters it is possible to choose operat-

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ing conditions for which the creation of metastable ions is negligible [5]. X-rays were observed with a Si(Li) detector with a diamond window and the resulting spectra for several values of q are presented in fig. 1. Two families of X-rays are observed, one of these in the range of 750–2000 eV and the other between 2500 and 6000 eV. Both families shift to higher energies with increasing incident ion charge state. The lower energy group, which dominates the spectra for lower incident charge states, is in the range expected for the filling of certain vacancies in the N shell while the higher energy group, which predominates for the higher incident charge states, is in the range that might be expected from the filling of M-shell vacancies.

3. Discussion

In order to determine the origin of the two families of lines, transition energies were calculated with Cowan's atomic structure codes [8] and Froese Fischer's Hartree–Fock program [9]. Within the resolution of this experiment the energy differences, i.e., the transition X-ray energies, provided by these programs agreed well and so the energies in fig. 2 were generated with the easier-to-use Froese Fischer program. This shows the expected X-ray energies for several transitions to the M and N shells as a function of the number of electrons, q, missing from the system. These numbers were obtained by removing the outer electrons sequentially. Another calculation (not shown) added electrons into outer lying states for $q = 55$ and lower. The results for such "hollow atoms" reduced the X-ray energies shown in fig. 2 by 100–200 eV. Energies of approximately 8000 and 4000 eV for the M and N X-rays, respectively, were calculated for decay from Rydberg states of highly charged Bi ions. For this reason the energies in fig. 2 cannot be used to assign definitive transitions to the peaks of fig. 1, e.g., decay of Rydberg states to the N levels can result in X-ray energies comparable to the more normal M–N transitions. Nevertheless, comparison of figs. 1 and 2 does establish the peaks between 750 and 2000 as having their probable origin in the filling of the N shell and those between 2500 and 6000 eV, to the filling of the M shell. No evidence is observed for decay into these shells directly from high Rydberg states, the continuum or the Fermi level of the gold.

Evidence is seen in the spectra with $q = 52$ and $q = 55$ for M X-rays being emitted from ions that enter the collision without the requisite M vacancies. This provides possible evidence for the existence of a dielectric process, such as that proposed by Schuch and coworkers. However, for this heavy projectile–target combination, the production of M vacancies through molecular promotions is also possible. Further experiments and calculations are planned to determine

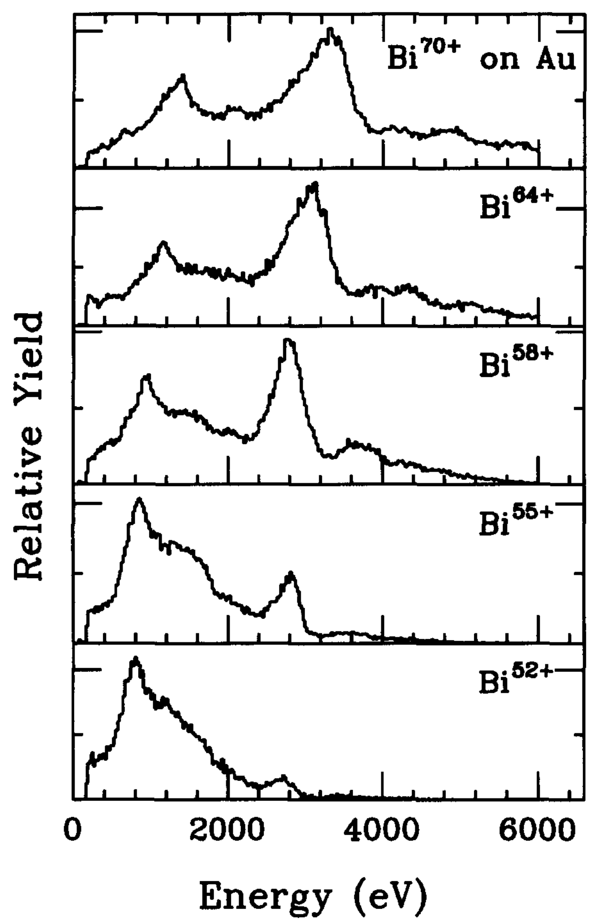

Fig. 1. X-ray spectra resulting from the impact of different Bi ion charge states on gold.

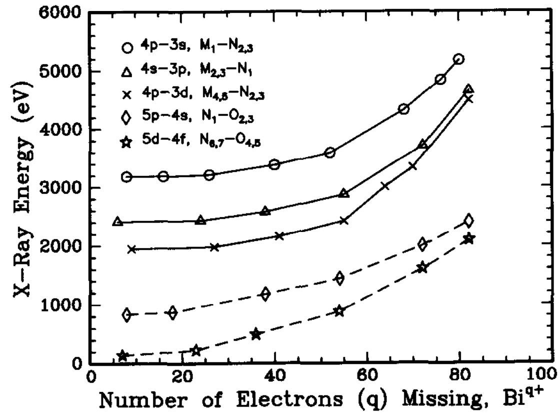

Fig. 2. The calculated energies for selected M and N X-rays plotted as a function of the Bi ion charge state.

whether or not molecular orbital effects are important in these collisions.

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